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GUIDANCE FOR INCINERATOR DESIGN AND OPERATION

VOLUME III

CREMATORS

APRIL 1989

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CREMATORS

Approvals Branch
Industrial Approvals - Air Section

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FOREWORD

This publication has been prepared by C.H. Beek, P.Eng. of the Approvals Branch to assist in the design, assessment and operation of crematoria incinerators and is one of a series of documents dealing with incinerator design and operation that have been prepared by the Ontario Ministry of the Environment. The other publications that are or will be available are:

- "Guidance for Incinerator Design and Operation, Summary and Update."
- "Guidance for Incinerator Design and Operation, Volume I (General)."
- "Guidance for Incinerator Design and Operation, Volume II, (Biomedical Waste Incinerator)."
- "Guidance for Incinerator Design and Operation, Volume IV (Cremators for Animal Shelters)."

The mention of trade names or commercial products in the report does not constitute endorsement or recommendation for use.

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INTRODUCTION

A cremator is one of the more complex types of incinerators which needs special attention due to the fact that the charge consists of a variety of different substances, each having its own combustion requirements.

Although numerous cremators have been built to date, their design has not always satisfied the specific requirements of the combustibles to be incinerated.

The purpose of this document is to assist engineers, manufacturers, suppliers, Ministry staff and other persons, in the design and evaluation of cremators which would meet requirements of the Ministry of the Environment.

This publication does not advocate a particular design but rather provides the basic engineering principles necessary for good incinerator design. Variations in design and the possibility of reclaiming energy from the exhaust gases to reduce operating costs are also discussed. In addition, various methods of control are discussed as well as the difficulties experienced by the operating personnel from a practical view point.

All new and existing cremators, or modifications and additions to existing cremators, must comply with the current Environmental Protection Act and Regulations and Guidelines made thereunder.

Normally, the owner is considered responsible for obtaining a Certificate of Approval from the Ministry of the Environment before any work commences, however, a

consultant, supplier or contractor may be delegated as an agent, but the responsibility will remain with the owner.

When an application for a Certificate of Approval is submitted, all pertinent data should be supplied including the following:

(1) a design drawing, showing all dimensions;
(2) a heat and mass balance;
(3) stack height, inside and outside diameter, material of construction, flue gas temperature and velocity;
(4) type of burners, maximum heat input, type of fuel;
(5) brief description of the modes of operation and how controlled;
(6) duration of one cremation cycle as designed;
(7) plot plan, showing the location of the cremator with respect to property lines and distance to the nearest occupied buildings off the property; and
(8) cremator room lay-out.
(9) if pollution control equipment is required, all pertinent data must be submitted such as type, size, design, flow rate, etc.

The room in which the cremator is to be located must comply with the applicable building codes and a municipal building permit must be obtained.

Since a variety of new materials have been or may be introduced to the casket manufacturing industry, it should be emphasized that acceptance of crematoria as described in this document is based on good combustion technology and the fact that no chlorinated plastic and fiber reinforced plastic (FRP) caskets are to be accepted for incineration in the cremator.

Cardboard caskets, impregnated with chlorinated compounds, must also be refused for incineration in a cremator.

However, should the owners of crematoria prefer the flexibility of receiving and incinerating the aforementioned materials, then "state of the art control" shall be incorporated into the crematorium design.

1 PURPOSE OF CREMATION

The purpose of cremation is to transform human remains (corpses) and associated materials into inert ashes and products of combustion. The process is carried out at sufficiently high temperatures to ensure that all pathogens and spores are destroyed and that the ashes are completely calcined.

Although cremation has been accepted in many parts of the world for centuries, it was not common practice in North America until the early nineteen sixties. Presently, the number of cremations carried out in Ontario is 25% of the total committals in this Province, (see Figure 1) and indications are that this percentage will increase in the future.

Cremation may be carried out for several reasons such as:

(a) personal preference;

(b) religious customs;

(c) economy;

e.g. if the remains must be shipped by public transportation (boat, train, aircraft, etc.), a corpse must be contained in a sealed lead casket and shipping costs may become prohibitive while the cost of shipping an urn (containing the ashes) would be a fraction of the cost.

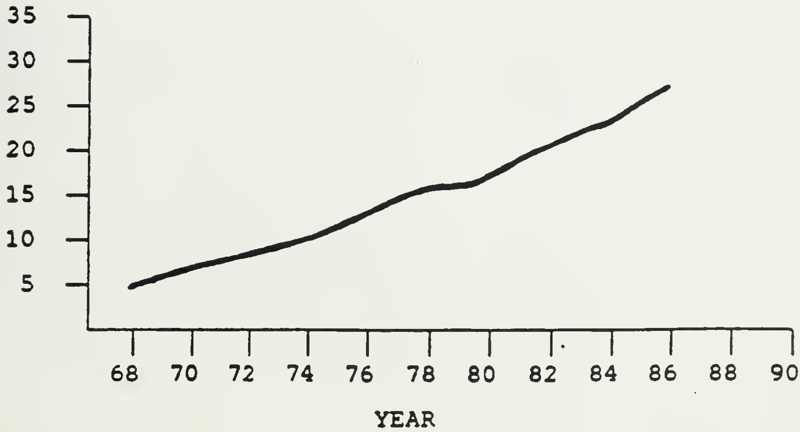
In some densely populated cities, the availability of a cemetery plot and the cost of maintaining it, may play a role in the decision to choose cremation.

COMPILATION OF TOTAL DEATHS AND CREMATIONS IN ONTARIO
(Obtained from the Ontario Coroner's Office)

TABLE 1

Year	Total Deaths in Ontario	Cremations in Ontario	% Cremation
1969	56,042	3,020	5.4
1970	57,321	3,595	6.3
1971	57,061	3,971	7.0
1972	59,499	4,795	8.1
1973	60,340	5,145	8.5
1974	61,030	6,001	9.8
1975	61,209	6,798	11.1
1976	61,220	7,259	11.9
1977	61,991	8,319	13.4
1978	61,450	9,128	14.9
1979	61,767	9,562	15.5
1980	63,092	10,554	16.7
1981	63,148	11,806	18.7
1982	63,696	12,488	19.6
1983	64,457	13,562	21.0
1984	64,550	14,608	22.6
1985	64,700	15,680	24.2

FIGURE I - PERCENTAGE OF CREMATIONS IN ONTARIO



2 CHARACTERIZATION OF CREMATOR CHARGE

2.1 The Corpse

Since cremation is not carried out on a selective basis, one may expect a wide range in body weight as well as in condition of the body, (due to sudden death, long illness, heavy medication, age, etc.) which will influence the burning characteristics. An average body weight and body condition must be selected for design purposes and at the same time some flexibility be incorporated to accommodate the under and over-weight corpses.

A survey, as shown in the "Report of the Task Group on Reference Man," (see References) indicates that the average body weight for design purposes may be taken as 65 kg. Since there are considerable differences in body conditions such as water content, fat to protein ratio, age, etc., an average condition has been selected for which the analysis is given in Figure 2.

The preparation of the corpse to be cremated is not different from the preparation for a conventional burial.

FIGURE 2 - COMPOSITION OF CORPSE "AS FIRED"

Water	37 kg	56.9%
Ash	3 kg	4.6%
Fat	12 kg	18.5%
Protein	13 kg	20.0%
TOTAL	65 kg	100%

In most cases nowadays (approximately 90%), the corpse is embalmed to retard decomposition.

Embalming involves the replacement of blood in the system with an embalming fluid which consists of a 1-2% formaldehyde solution.

2.2 The Casket and Other Materials

2.2.1 Basic Materials of Construction

In most countries, a casket or coffin is used to contain the corpse to be buried or cremated. A casket (primarily used in North America) is a rectangular box (usually wood) in which a corpse is put to be buried or cremated. A coffin (predominantly used in Europe) differs from a casket in that it is tapered towards the bottom end and slightly tapered towards the head end of the box.

Caskets and coffins are made of a variety of materials such as solid wood, veneered particle board, cloth covered plywood, fibre or chipboard, reinforced and/or impregnated cardboard, dense styrofoam, FRP (fibre reinforced plastic), polyurethane, lead and steel. Only a few of these are considered suitable for cremation since the majority of cemeteries accept only caskets and coffins for cremation which are made of combustible materials which will burn at a controllable rate and do not create any toxic fumes.

Caskets and coffins constructed of solid wood, veneered fibre or particle board and cloth covered plywood are most suitable for cremation. Reinforced cardboard caskets have not established a market at present; however, developmental work is being conducted to improve both design and

reinforcement materials until a reliable product can be made
This could then also be acceptable for cremation, provided t
chemicals used for reinforcement are acceptable.

Due to the various materials used for construction, the type
casket will affect the burning characteristics and the overa
duration of the burning cycle. A standard casket has inside
measurements of approximately 200 cm long by 55 cm wide and
high. The outside measurements will depend on the type of c
and the wall thickness. The largest casket available from
regular stock is approximately 215 cm long by 75 cm wide and
60 cm high (outside dimensions). Figure 3 shows the approxi
weight and composition of various caskets.

TYPICAL WEIGHT AND COMPOSITION FOR VARIOUS CASKETS

Type of Casket	Weight (Bedding) not included)	COMBUSTIBLES				
		wood	lacquer	cloth	water	as
Solid hardwood	53 kg	49.0 kg	1.0 kg	-	2.5 kg	0.5
Veneer Covered Particle Board	53 kg	49.0 kg	1.0 kg	-	2.5 kg	0.5
Cloth Covered Pine Wood	32 kg	29.0 kg	-	1.0 kg	1.7 kg	0.3
Cloth Covered Plywood	32 kg	29.0 kg	-	1.0 kg	1.7 kg	0.3

Figure 3

2.2.2 Finishes

The finish on a casket varies with the type of casket and the quality. Solid hardwood caskets and veneered particle board caskets are usually finished like fine furniture.

The outside surfaces are treated with several coats of lacquer (approximately 4 litres) which would, after drying, amount to approximately 1 kg.

For cloth covered plywood and pinewood caskets, a lightweight canvas is used to completely hide any wood. The canvas is usually dyed light grey and approximately 7 m^2 of cloth are used for one casket. This lightweight canvas weighs approximately 135 g/m^2.

2.2.3 Furnishings and Clothes

The inside furnishings of a casket usually consist of the following:

(a) mattress and mattress cover;
(b) lining and padding;
(c) pillow;
(d) decorative ruffles.

The material used for the mattress is usually excelsior (short fine curled shavings of softwood) with the cover made of cotton. The lining and other furnishings can be made of any fabric and the quality is usually matched with the quality of the casket.

The pillow is usually filled with a cotton material which can be formed into any required shape without springing back.

The average weight of the total furnishings of a casket is approximately 11 kg with an additional 2 kg for clothing.

2.2.4 Miscellaneous Extraneous Material

It has in the past been noticed that a casket contained extraneous material such as empty or partly filled embalming fluid cans, pathological remains from other sources, rubber gloves or any other material which may find its way into the casket.

This is undesirable practice and although these incidents are few, the fact that it has happened in the past and may happen again should serve as a warning to both the manufacturer of the incinerator and the operator. A word of caution should be written in the operating manual. A pressurized container may explode during incineration and the operator should be made aware of the consequences such as a sudden release of additional combustible materials, damage to incinerator etc.

3 CREMATION TECHNOLOGY

3.1 General Process and Design

A cremator usually consists of 3 chambers, the primary chamber, the mixing chamber and the secondary chamber, each having its own specific purpose.

The primary chamber will contain the casket and should be equipped with a minimum of two burners to ignite the casket and supply additional heat to maintain a minimum temperature of 800°C to vaporize all combustible material and moisture contained in the charge. Furthermore, the auxiliary heat supply must be capable of completely calcining the bones in the final burning cycle when all combustible material is gone.

Both ignition burner(s) as well as the afterburner must be designed to be capable of maintaining a temperature of 800°C and 1100°C respectively. The afterburner may be operated at a lower temperature but not lower than 1000°C at all times.

Although a significant amount of combustible matter is incinerated in the primary chamber, it is not necessary to achieve complete combustion of the gases in this chamber. Instead, it is preferred to have a controlled burning rate which would allow the incinerator to operate more closely to design specifications. The practice of designing for a burning rate of x kg/h assuming that the same amount of material of the same composition will be consumed per time unit, has almost always led to unsatisfactory performance and such a design would certainly not be capable of handling excessive burning rates (which do occur in practice). In a cremator, different materials may be burned separately, or in combination, at distinctly different times in contrast with a multiple waste incinerator where the "fuel" is mixed. To be more specific, during the first two minutes of the cycle, only lacquer is incinerated at an approximate burning rate of 30 kg/h. During the following 15 minutes (for a solid wood casket) only wood is incinerated at an approximate rate of 90 kg/h till the casket breaks open. At this moment, a large amount of gasified material is released from the contents of the casket and at the same time, the lighter material such as pillows, clothes, excelsior, lining etc. is burned almost instantaneously, resulting in a very high burning rate. During the next part of the cycle, a combination of primarily wood and tissue are burned unless some other extraneous materials are present. During the last part of the cycle, when most combustible material has been consumed, the bones are being calcined which requires very little oxygen but a high temperature.

Consequently, the primary chamber fuel/air supply must be quite flexible and the best way to achieve this is to use controls which will modulate the air and auxiliary fuel independently such that a minimum temperature of 800 °C may be maintained.

The mixing chamber receives all gases and vapours from the primary chamber and its main purpose is to thoroughly mix the gases before they enter into the secondary chamber. Supplementary air, necessary for the complete combustion of these gases, may be introduced in the mixing chamber or in the secondary chamber itself.

The secondary chamber is equipped with a burner (usually called afterburner) to maintain a temperature of at least 1000°C throughout this chamber with a retention time of 1.0 second, measured from the flame front of the burner to the thermocouple, to ensure complete combustion of the less volatile material and the destruction of pathogens.

The selection of the afterburner is quite important since it must cope with a wide range of heat supply. To save energy and to avoid large temperature variations, a fully modulating burner, controlled by a thermocouple or other suitable automatic temperature sensor should be selected. This sensor should be located at a point where the gases (at maximum load capacity) have completed a retention time of 1.0 second, measured from the flame front of the secondary burner.

The air for combustion of the charge should be supplied by a fan rather than relying on natural draft air ports.

In many instances, a low chimney is preferred for various reasons. In those cases a mechanical draft inducer should be installed to maintain 0.25 cm W.G. at the charging door.

3.2 Process Stages

In a cremator, 5 distinct process stages can be identified, with each stage burning a different type of material, having its own distinct fuel and air requirements.

Figure 4 shows the various stages of the cycle.

OVERALL FUEL AND AIR REQUIREMENT FOR VARIOUS STAGES

STAGE	FUEL	AUXILIARY FUEL REQUIREMENT	AIR REQUIREMENT
1	lacquer or cloth	very low	high
2	wood	low	medium
3	wood and furnishings	very low	high
4	wood and tissue	medium	medium
5	bone	high	low

Figure 4

As mentioned before, it is not necessary to obtain complete combustion of the gases in the primary chamber. Instead, it is much better to accomplish this in the secondary chamber where more controlled conditions prevail in order to satisfy the requirements of the three T's of combustion (time, temperature and turbulence). The primary chamber should be considered as a chamber where the charge is converted into the gaseous state (except for the bones and ashes). The rate of combustion can be controlled by the regulation of the air supply and the auxiliary fuel to maintain a temperature of approximately 800 °C, sufficient to gasify the charge within a certain time.

When a cremator is to be used from a cold start, the secondary chamber should be preheated till the minimum operating temperature of 1000°C has been reached at the thermocouple to prevent the discharge of partially oxidized combustibles due to their contact with relative cool chamber surfaces.

It is not considered necessary to preheat the primary chamber because this may create more problems than it will solve (e.g. burning rates exceeding design rates). Should a cremator be used primarily for continuous operation, the high rate of volatilization due to a hot primary chamber should be taken into account in the design.

To determine the maximum and minimum air supply and burner capacities, each stage of the cycle should be considered separately.

<u>Stage 1</u> - Burning of lacquer, cloth etc.

When the primary chamber is cold (ambient air temperature), the casket can easily be put into the primary chamber and positioned properly. This is usually done by putting 3 or 4 pieces of 5 cm diameter pipe on the floor of the primary chamber and then pushing the casket in place, using the pipe as roller bearings. The burners can now be started to ignite the lacquer (or cloth) and are usually left on till a good fire has been established.

Since the lacquer volatilises very easily and will burn off during the first few minutes, a lacquer burning rate of approximately 30 kg/h will result during that short period. If this were not accounted for in the incinerator design with respect to air requirements, an unacceptable discharge of black smoke from the stack would be anticipated during the initial burning period.

However, if the cremator is used on a continuous basis, the refractory in the primary chamber remains very hot and the radiant heat will ignite the lacquer almost instantaneously. The charging of the casket is done in the same way as before but the operator has to be more careful under these circumstances. When the casket has been pushed into the primary chamber for half its length, most of the lacquered surface is already on fire which makes it very difficult for the operator to stay near the opening due to the radiant heat of the refractory and the flames of the burning lacquer. In this mode, the lacquer takes approximately 1 minute to burn, resulting in a lacquer burning rate of 60 kg/h. No auxiliary fuel is required during this period. Air is usually supplied by the burner fans (burners in the "on" position with the fuel valves closed).

<u>Stage 2</u> - Burning of wood.

After the lacquer has been combusted, only wood is being burned at an approximate rate of 90 kg/h and usually, no auxiliary fuel is required. After approximately 15 minutes (depending on the type of casket) the structural strength of the casket has been weakened by the fire to such an extent that the walls can no longer support the structure, resulting in the collapse of the casket. This is a critical point in the cycle as the composition of the fuel has now changed.

<u>Stage 3</u> - Burning of wood and furnishings.

As soon as the casket collapses, the furnishings (bedding, clothes, lining etc.) ignite almost immediately, increasing the burning rate and consequently the air requirement. If the additional air for the furnishings is not designed for in the secondary chamber, another short period of an unacceptable discharge from the stack will occur.

The furnishings and clothing, weighing approximately 13 kg, will usually be burned in approximately 5 minutes, which means a burning rate of about 156 kg/h. Although various materials are being used for the furnishings, they all may be considered to be cellulosic materials.

Stage 4 - Burning wood and tissue.

At this stage of the cycle, the burning rate of the wood has been reduced considerably since most of the volatiles in the wood have been consumed (reducing the wood to char), and auxiliary heat is required to maintain a desired burning rate. In the first part of this stage, the body fluids are vaporized and the readily combustible material such as body fat and protein are incinerated together with what is left of the wood. The various kinds of tissue (brain, lungs, organs, etc.) are more difficult to incinerate and require a higher temperature (650 °C - 700 °C). As those parts of the body and the casket nearest to the floor of the primary chamber have not sufficiently been subjected to the heat and combustion air, it is common practice to rake the remains during the second half of this stage to promote good exposure.

At the end of this stage, when all combustible material is gone, part of the bones have already been calcined.

Stage 5 - Calcining of the Bones.

At this point, only bones are left to be calcined which requires very little air but a high temperature. There is some marrow left in the bones but, due to the small quantity compared to the overall fuel requirements, can be neglected for combustion purposes. Usually, the calcining of the bones takes approximately 20-30 minutes. If no

more cremations are to be done, the auxiliary fuel supply in both chambers is turned off after this period while the air supply is left on for another 30 minutes or so to cool the unit sufficiently for removal of the ashes. The ashes are collected in a metal trough and further cooled to room temperature. The trough is then emptied onto a sieve to separate large unwanted objects such as casket hardware and large nails. Smaller metal parts are removed from the ashes by means of a magnet.

Large pieces of bone are crushed with a metal roller and added to the ashes which are then put in a plastic bag. The plastic bag is put in a metal container which can now be stored in a columbarium or returned to the family if so desired.

3.3 Operational Difficulties

Various operational difficulties, relating to the design, have been encountered by the operating personnel of cremators.

The problems most often experienced by cremator operators can be identified as follows:

(1) Insufficient control of the burning rate in the primary chamber.
(2) Insufficient air supply in the secondary chamber for complete combustion of the gases.
(3) Combustion rate too low during the burn-down period.
(4) Charging a lacquered casket into a hot primary chamber.
(5) Removal of ashes from a hot primary chamber.

Problems (4) and (5) are experienced only when two or more cremations are performed with a relatively short time between each cremation.

Most, if not all, of the above mentioned problems can be eliminated through proper attention to the operational aspects of the design which includes provision for additional air supply for extreme conditions.

A brief discussion of each of the five problems follows.

1. Many operators have experienced cases where the casket burns too quickly, resulting in smoke emissions from the chimney, and find themselves not being able to correct the problem. Too much excess air is introduced into the primary chamber, resulting in an accelerating burning rate of the casket. If the air supply is not controlled automatically, the operator should have control of the air supply to the primary chamber over a suitable range, e.g. from 50%-100% of stoichiometric air supply.

2. As mentioned before (section 3.2), the secondary chamber should be designed such that complete combustion takes place under all conditions. The air supply rate should be sufficient to deal with peak loads of combustible gases entering the secondary chamber. The air supply should be independent of the burner air supply so that it is not controlled by the burner thermocouple.

3. To promote rapid burning throughout the cycle, consideration should be given to stage 4 - burning wood and tissue (section 3.2).

During this part of the cycle, combustible material lies on the hearth in a pile, making it difficult for the air to penetrate and raking and spreading is often required.

To alleviate this problem, an air diffuser system could be incorporated into the hearth, supplying underfire air. Relatively small holes and sufficient air pressure would prevent any ashes from plugging the holes.

4. When a lacquered casket or any casket of highly inflammable material must be charged into a hot primary chamber due to lack of time to properly cool the primary chamber, the operator is faced with the problem of being exposed to a very high temperature (radiant heat from the refractory) while handling a casket which is already burning outside the primary chamber. One solution would be the addition of a removable vestibule, having a side door for easy charging and not requiring additional space in front of the cremator (see Figure 6). The casket is placed in the vestibule, the side door closed and then the charging door of the cremator opened while the casket is pushed into the primary chamber by means of an internal transportation system (ram, chain, motorized rollers etc.).

   In this way, the casket can be handled safely by the operator without the danger of flashback or being exposed to heat and smoke.

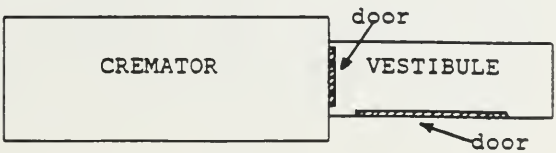


Figure 6

5. Operation of a cremator on a continuous basis necessitates removal of the ashes before the next casket is charged.

   With some cremator designs, the ashes can only be removed from the primary chamber through the charging door or a small door in the side wall and it is therefore necessary to let the unit cool down, sometimes for several hours, before the ashes can be handled comfortably.

   In the meantime, the cremator is out of service, thereby reducing the overall daily capacity of the unit.

   It is, therefore, important to incorporate facilities allowing removal of the ashes from the primary chamber shortly after completion of the cycle. This might be achieved by having an opening at the end of the hearth through which the ashes can be pushed. From here the ashes drop into an ashpit where they are allowed to cool down while the next cremation is in progress.

Fuel Savings

To have better control of the operation while saving energy, all burners should be fully modulating and controlled by thermocouples, set for 800°C in the primary chamber and 1000°C in the secondary chamber. For good heat distribution, especially during the calcining stage, the primary chamber should be equipped with a minimum of two and preferably three burners. During the calcining stage, when little air is required, the air supply for combustion of the charge could be reduced by 50%, resulting in a lower fuel consumption.

Another method of reducing fuel costs is to preheat the air for combustion. This could be done by placing an insulated jacket around the outside of the cremator, leaving an air space between the unit and the jacket through which combustion air is drawn. It is also possible to reclaim some of the heat from the flue gases by using a heat exchanger through which combustion air is drawn.

4 CREMATOR CONSTRUCTION

4.1 Casings

Cremator casings may be constructed in different ways, the two basic types being;

(a) Packaged Units

This type of casing consists of a metal frame, enclosed by sheet metal plates. The insulation and refractory material is located inside the metal frame. Care should be taken that no parts of the metal frame are exposed to the high temperatures in the cremator to avoid warpage and cracks.

This type of casing is mainly used for a standard design production unit and can be completely built and tested in the manufacturing plant.

(b) Fixed Units

Casings of this type are built on the site and do not necessarily require a heavy steel frame. The outside walls can be made of brick and the unit can be "custom made".

In both designs, provision should be made for expansion due to the high temperatures involved.

The refractory material used should be rated for temperatures of at least 1350°C and should be equivalent in quality to firebrick, conforming to ASTM designation C-24, P.C.E. 31-32.

4.2 Refractory and Insulation

Refractory:

A cremator, like any other furnace, should be made with good quality high heat refractory material. Although numerous variations are possible, (firebrick, refractory tile, monolithic etc.) the selected refractory material should at least have the following properties.

1. Ability to withstand High Temperatures

Although the unit is to be designed for a temperature of 1100°C, temperatures in the primary chamber and secondary chamber may rise (locally) well above 1100°C for short periods of time.

2. Low Heat Capacity

The operating temperature will be reached in a shorter time and the burner capacity may be smaller.

3. Wear and Impact Resistance

When the casket is charged into the primary chamber, the walls may receive some abuse. Also, when the remains are raked and when the ashes are removed, the refractory material is subjected to scraping by the metal tools used.

4. Reasonable Resistance to Thermal Shock

When the charging door is opened during or after the process, a large amount of cold air rushes in, chilling the surface layer of the refractory material, which can ultimately lead to stress cracks.

The thickness of the walls depends on the insulating qualities of the refractory material but should be sufficient to prevent excessive interface temperatures.

Insulation:

Insulation may be provided by using ventilated air spaces, loose fill for roofs only, block insulation, insulating concrete or any combination of these systems which will ensure continuous protection of the surface, casing or wall involved.

Insulation should be selected for characteristics which will endure high interface temperatures without deterioration and provide suitable coldface temperatures.

The outside wall temperatures should be below 80°C for comfort and safety reasons.

4.3 Burners

Type of Burner

Past experience with cremators indicates that natural gas or propane is the preferred fuel for auxiliary heat, hence all cremators in Ontario are equipped with gas burners. Nozzle mix power burners should be used to obtain a stable turbulent flame with a high velocity for better furnace recirculation. Most burners of this type have a short flame length and therefore do not require large combustion chambers.

Location of Burners

(a) Primary Chamber

Burners in this chamber should be located so that the flame is directed towards the charge. This is especially important during the burndown and calcining stages when high temperatures are required.

If the burners are to be installed in the side walls, they should be directed to the longitudinal centreline of the hearth. If located in the roof, they should be located directly over the charge. Some manufacturers have used remotely controlled directional burners which allow the operator to change the direction of the flame as needed.

It is important that the entire charge is enveloped by the flame and therefore multiple burners are preferred instead of a single burner.

Experience with many cremators has shown that 3 burners in the primary chamber give very satisfactory results.

(b) Secondary Chamber

Usually one burner in this chamber is sufficient and it should be located such that all incoming gases from the mixing chamber must pass through the flame for intimate contact.

All burners should be provided with an automatic ignition device and an approved automatic flame failure shut-off valve.

4.4 Controls

It is generally agreed that a manually controlled system is usually lacking the required degree of response that can be obtained with automatic controls, especially if the operator is not in constant attendance.

Modern cremators may be equipped with various controls, with each acting either independently or as an integral unit to form a control system. The purpose of any control system is to improve the performance of the cremator.

Since operating conditions in a cremator are changing continuously, a closed loop control system should be selected to control such variables as temperature and air supply. One of the most widely used temperature control elements is the thermocouple, actuating a fully modulating burner input valve. The air supply can be controlled by using an oxygen analyzer in the flue gas which would actuate the air supply fan.

The reference input should be 100% excess air. When the air supply is reduced, the temperature of the gases will increase and upon reaching 1000°C, the burner input will be reduced by the temperature sensing device.

The installation of a dual control system as mentioned would reduce the overall auxiliary fuel consumption considerably while the required controls would pay for themselves with the savings realized from the reduced fuel consumption.

If it is intended to operate the cremator without a full-time attendant, a timer may also be installed to control the duration of the cycle, closing off the gas supply after the pre-set time has elapsed and leaving the primary chamber air supply on for half an hour or so till the unit has cooled off sufficiently for safe ash removal.

4.5 Auxiliary Equipment

To improve the operation of a cremator, auxiliary equipment may be required. The principal auxiliary equipment is as follows:

a) Mechanical draft equipment;
b) Ash removal system;
c) Temperature indicators;
d) Observation ports; and
e) Breeching damper.

To appreciate the purpose of the auxiliary equipment, a brief discussion will follow.

(a) Mechanical draft eliminates the reliance on stack temperature, stack height and ambient conditions. Usually, mechanical draft is created by means of a fan delivering the air to the inlet of the cremator (forced draft) or by means of a fan located at the outlet of the cremator (induced draft). If an induced draft system is used, the exhaust gas temperature must be reduced to a temperature that can be handled by the fan without causing thermal damage. This is usually done by introducing ambient air into the stack before the fan inlet or alternatively the fan may be specifically designed to handle high temperature gases.

Other methods of creating induced draft are the use of a venturi tube or a power jet fan, both systems using additional air.

A forced draft system is more economical than an induced draft system as it requires less fan power (smaller fan). However, if the cremator is not air-tight and operates at a higher than atmospheric pressure, gases may leak into the crematorium room which is unacceptable.

(b) Ash removal systems should be designed to make it easy for the operator to collect all ashes. Different methods are employed and depend partly on the design of the cremator and the number of cremations carried out per day.

If only one cremation takes place during a day, the operator may leave the ashes in the cremator till the next morning when they can be conveniently removed with an industrial type vacuum cleaner or with a long handled broom. If two or more cremations take place during the same day, the ashes must be removed after each cremation to ensure that they will not be mixed with ashes from the next committal. In this case, the two previous methods cannot be used due to the high temperature in the primary chamber. Often, a refractory lined door is provided in one of the side walls of the primary chamber. The ashes are pushed to the back of the primary chamber with a hoe on a long metal handle. A metal tray is hung on the side wall below the ash door and the ashes can now be removed from the primary chamber. A steel wire brush is used to remove the finer ash particles.

If the design of the cremator does not allow an ash door in one of the side walls, the ashes must be removed through the charging door opening.

(c) Temperature indicators must be used to provide the operator with feedback information on the burners and air supply fan to evaluate the overall performance of the unit. They may also be considered a safeguard, preventing the refractory and other components of the cremator from reaching extreme temperatures.

(d) Observation ports should be located in the primary chamber charging door such that the entire chamber can be observed. The purpose of an observation port is to allow the operator to monitor the combustion process without having to open the door. The opening of the door would allow a large volume of air to enter the primary chamber, resulting in a rapid drop in temperature and creating conditions in the primary and secondary chambers which may be beyond the design limits of the cremator. It may also cause stress cracks in the refractory and, if repeated regularly, will eventually lead to the disintegration of the wall surfaces, thus shortening the life of the refractory considerably. Another advantage of the observation port is that the operator is able to determine when and how to rearrange or rake the charge. He can get the necessary tools ready and when the door is opened, he knows exactly what to do, thereby reducing the time of cold air infiltration to a minimum.

(e) A breeching damper is recommended to eliminate the draft while the chimney is still hot. When more than one cremation is to be done on the same day, the ashes must be removed shortly after the first cremation is completed while the unit is still very hot. By closing the breeching damper, the draft through the unit is eliminated and when the charging door is

opened, the ashes can be removed from the primary chamber without being entrained in the air stream which would normally enter through the charging door when the damper is not closed. A breeching damper also prevents rapid cooling of the hot refractory walls.

For cremators depending on natural draft as a means of air supply, the breeching damper can also be used to regulate the air supply within limits. If a breeching damper is to be installed, local authorities should be contacted regarding safety regulations for combustion units.

5 STANDARDS AND POLICY GUIDELINES

The performance of a cremator should be measured against the standards issued by the designer and the standards issued by the Ministry of the Environment.

In addition to the above, the cremator should meet the incinerator guidelines issued by the Ministry of the Environment:

(1) The auxiliary burners, installed in a cremator, shall be of sufficient capacity to be capable of maintaining a temperature of 800°C in the primary chamber and 1100°C in the secondary chamber;

(2) The secondary chamber shall not be operated at a temperature lower than 1000°C at any time;

(3) The afterburner(s) shall be fully modulating with a "hold fire" setting to ensure the presence of a flame in the secondary chamber throughout the entire cycle.

(4) The temperature in the primary chamber shall be maintained at 800°C for at least 30 minutes during the last part of the cycle to ensure complete calcination and sterilization of the bones;

(5) The retention time of the gases in the secondary chamber, measured from the flame front of the burner and calculated at 1000°C, shall not be less than 1.0 second;

(6) The flue gases, analyzed before the barometric damper (if so equipped), shall contain not less than 6% oxygen, measured on a dry basis; and

(7) The velocity of the gases in the mixing and secondary chamber shall provide a high degree of gas phase turbulence.

(8) The incinerator shall be equipped with a temperature recorder/controller to control and record the temperature in both the primary and secondary chamber.

APPENDIX A-1

Combustion Calculations - Heat and Mass Balance

Since the calcining of the bones takes approximately 30 minutes and the complete cycle 90 minutes, the design capacity of the cremator should be based on the fact that the charge is consumed in one hour. The charge will consist of:

Casket, Furnishings and Clothes	=	67 kg/h
Body	=	65 kg/h
TOTAL	=	132 kg/h

However, if the cremator would be designed for the above noted burning rate, the unit would not be capable of handling the peak burning rates and visible smoke would be emitted from the chimney, which is unacceptable for a cremator.

Assuming that adequate turbulence is provided, one may design for 100% excess air for the charge at peak burning rates while the burners usually operate with 20% excess air at full capacity. To determine the minimum air supply required for the charge, the maximum burning rates should be considered.

When assuming that several cremations are performed during a day, the worst conditions (highest burning rates) will occur when a casket is charged into a hot chamber. Under these conditions, the following burning rates would result:

Lacquer (1 kg in 1 minute)	=	60 kg/h
Wood (20-25 kg in 15 minutes)	=	90 kg/h
Furnishings and clothes (13 kg in 5 minutes)	=	156 kg/h

AIR REQUIREMENTS FOR THE CHARGE

Lacquer

Max. burning rate		60	kg/h
Stoichiometric air		4.2	kg/kg
Air @ 100% excess			
(60 x 4.2) x 2	=	504	kg/h

Wood

Max. burning rate		90	kg/h
Stoichiometric air		4.88	kg/kg
Air @ 100% excess			
(90 x 4.88) x 2	=	878	kg/h

Furnishings and Clothes

Max. burning rate		156	kg/h
Stoichiometric air		4.82	kg/kg
Air @ 100% excess			
(156 x 4.82) x 2	=	1504	kg/h

This clearly indicates that the highest air supply rate is required when burning the furnishings. Therefore, the minimum air supply required is 1504 kg/h.

Primary Chamber

Composition of Charge

Lacquer	1 kg
Wood	53 kg
Furnishings and Clothes	13 kg
Body	65 kg
TOTAL	132 kg

Gross Heat Input from Charge

Lacquer	1 kg/h x 23,238 kJ/kg	=	23,238 kJ/h
Wood	53 kg/h x 16,266 kJ/kg	=	862,098 kJ/h
Furnishing and Clothes	13 kg/h x 18,590 kJ/kg	=	241,670 kJ/h
Body	65 kg/h x 6,274 kJ/kg	=	407,810 kJ/h
TOTAL		=	1,534,816 kJ/h

A literature search indicates that various heating values for the corpse are available, depending on condition. A value of 6,300 kJ/kg is assumed to be a reasonable average value.

Heat Not Available to Raise the Temperature of the Gases

Convection and Radiation (assume 2% of input)		
0.02 x 1,534,816 kJ/h	=	30,696 kJ/h
Latent heat in H_2O from charge		
2.5 kg/h x 2,463 kJ/kg (casket)	=	6,158 kJ/h
37 kg/h x 2,463 kJ/kg (corpse)	=	91,131 kJ/h
Latent heat in H_2O from combustion		
89 kg/h x 0.556 kg/kg x 2,463 kJ/kg	=	121,879 kJ/h
Sensible heat in ashes		
3.5 kg/h x 0.92 kJ/kg°C.(800°C-15°C)	=	2,528 kJ/h
TOTAL	=	252,392 kJ/h

Net heat available from charge to raise the temperature of the gases to 800°C.

$$1,534,816 - 252,392 = 1,282,424 \text{ kJ/h}$$

<u>Weight of Gases Required to maintain 800°C</u>

$$Q = \dot{m}.Cp.\Delta T$$

(assume average Cp = 1.21 kJ/kg.°C)

$$1,282,424 = \dot{m} \times 1.21 \times (800 - 15)$$

$$\dot{m} = \frac{1,282,424}{1.21 \times (800-15)} = 1,350 \text{ kg/h}$$

where:
- Q = net heat available to heat gases in kJ/h
- $\dot{m}$ = total weight of gases in kg/h
- Cp = specific heat of the gases in kJ/kg°C
- ΔT = temperature difference in °C

<u>Weight of Gases Supplied</u>

from charge	132 - 3.5	=	128.5 kg/h
air for combustion	0.5 x 1504	=	752.0 kg/h
	TOTAL	=	881 kg/h

<u>Air Required for Cooling</u>

$$1350 - 881 = 469 \text{ kg/h}$$

If this excess air for cooling is not supplied, the calculated temperature in the primary chamber would be

$$\Delta T = \frac{Q}{\dot{m}.\ Cp} = \frac{1,282,424}{881 \times 1.21} = 1,203°C$$

$$T = \Delta T + 15 = 1203 + 15 = 1,218°C$$

However, this temperature will not likely be reached in the primary chamber without auxiliary fuel because of:

(a) additional heat losses which we have not considered yet; and

(b) rapid evaporation of moisture during highest heat release rate.

For these reasons, additional air for cooling is seldom used.

(a) <u>Heat Storage in Walls</u>

During the cremation process, the refractory and/or firebrick does not usually reach equilibrium conditions, especially not when the process is started with a cold or cool primary chamber. Part of the heat is used for heating the brickwork, which could take 8 hours or more, depending on the construction of the unit.

<u>Example:</u>

Assume the following,

Walls are made of 17.8 cm refractory + 7.6 cm insulblock

hot face temperature	1000°C
interface temperature	798°C
cold face temperature	85°C
density of refractory	2,084 kg/m^3
density of insulblock	481 kg/m^3
Cp of refractory	1.17 kJ/kg.°C
Cp of insulblock	0.92 kJ/kg.°C

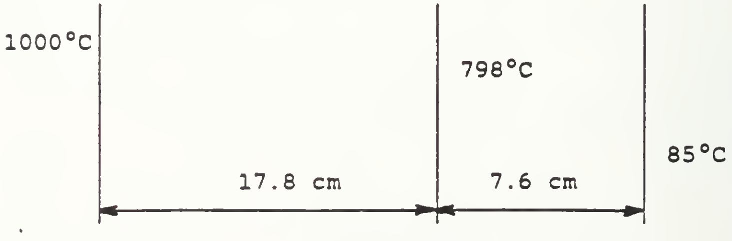


Figure 5

At equilibrium conditions, the mean temperature across the refractory would be:

$$\bar{T} = \frac{1000 + 798}{2} = 899°C$$

The mean temperature across the insulblock

$$\bar{T} = \frac{798 + 85}{2} = 441.5°C$$

The heat storage in the wall, corresponding to 1 m^2 wall area would be:

$$Q = m.Cp.\Delta T \quad \text{(assume ambient temp. is 15°C)}$$

$$Q_1 = (1x1x0.178x2084)(1.17)(899-15) = 383,668 \text{ kJ}$$

$$Q_2 = (1x1x0.076x481)(0.92)(441.5-15) = 14,344 \text{ kJ}$$

$$Q = 383,668 + 14,344 = 398,012 \text{ kJ}$$

Inside dimensions of the primary chamber

Length 2.44 metres

Width 1.22 metres

Height 0.91 metres

The total exposed wall area would be:

$$2(2.44x0.91) + 2(2.44x1.22) + 2(1.22x0.91) = 12.61 \text{ m}^2$$

Total heat storage = 12.61(383,668+14,344) = 5,018,931 kJ

Although the rate of heat absorption by the walls is not linear, assume that 10% of the total heat storage occurs in the first hour.

During this period, the temperature of the outside walls has not increased significantly and therefore, when a cremator is started from cold, the heat loss from the outer surfaces to the ambient air may be assumed negligible compared with the heat loss due to heat storage.

A new heat balance for the primary chamber would be as follows:

Gross heat input   1,534,816 kJ/h (from page 33)

Heat not available to raise temperature of gases

heat storage 0.10 x 5,018,931	=	501,893 kJ/h
latent heat in H_2O from charge	=	97,289 kJ/h
latent heat in H_2O from combustion	=	121,879 kJ/h
sensible heat in ashes	=	2,528 kJ/h
TOTAL	=	723,589 kJ/h

Net heat available

1,534,816 - 723,589 = 811,227 kJ/h

$$\Delta T = \frac{Q}{m.\ Cp} = \frac{811,227}{881 \times 1.21} = 761^{\circ}C$$

$$T = 761 + 15 = 776^{\circ}C$$

(b) Evaporation of Moisture and Heat Requirement

As was shown in section 3.2, the highest burning rate occurs when the furnishings are being burned and one would expect a sharp rise in temperature. However, from numerous observations, this does not occur since part of the body fluid is being evaporated at the same time which could be as much as 15 kg during this period.

Maximum auxiliary heat requirement occurs during the calcining cycle when no combustibles are left in the primary chamber.

The useful heat from the burner(s) in each chamber must equal the total heat required in each chamber at 800°C and 1000°C respectively.

<u>Heat Required in Primary Chamber</u> (During Calcining)

Convection and radiant (outside wall @ 85°C) heat through walls etc.	= 30,000 kJ/h
Sensible heat in the gases = 752 x 1.0456 x (800 - 15) leaving primary chamber	= 617,239 kJ/h
TOTAL	= 647,239 kJ/h

From Appendix A-3, page 49

1 m^3 of natural gas supplies 19,493 kJ of useful heat when combusted at 800°C with 20% excess air.

Volume of natural gas required: $\frac{647,239}{19,493} = 33.2\ m^3/h$

Density of natural gas = 1.4 m^3/kg

Weight of natural gas required = $\frac{33.2}{1.4} = 23.7$ kg/h

Heating value of natural gas is 37,256 kJ/m^3

Burner capacity in primary chamber required

33.2 x 37,256 = 1,236,899 kJ/h

Since the gases, coming from the primary chamber, have already been heated to 800°C, we have to provide heat in the secondary chamber to raise the temperature of the gases to 1000°C and also account for the heat loss through the walls of the secondary chamber.

<u>Gases Entering Secondary Chamber</u>

Air from primary chamber	=	752 kg/h
Gases from primary burner(s) at 20% excess air (page 48) 33.2 x 14.98	=	497 kg/h
		1,249 kg/h

The heat loss through the walls in the secondary chamber is approximately the same as in the primary chamber. We now have to raise the temperature of the gases to 1000°C.

Convection and radiant heat through walls	=	30,000 kJ/h
Sensible heat required for gases to 1000°C		
1,249 x 1.0456 x (1000-800)	=	261,190 kJ/h
TOTAL		291,190 kJ/h

from Appendix A-4, page 53

1 m³ of natural gas supplies 15,500 kJ of useful heat when combusted at 1000°C with 20% excess air.

Volume of natural gas required: $\frac{291,190}{15,500} = 18.8\ m^3/h$

Density of natural gas = 1.4 m^3/kg

Heating value of natural gas is 37,256 kJ/m^3

Burner capacity required in secondary chamber during calcining stage:

18.8 x 37,256 = 700,413 kJ/h

Weight of natural gas required $\frac{18.8}{1.4} = 13.4$ kg

Overall Heat and Mass Balance

The following calculations are for the first hour, assuming that no combustible material is left after one hour.

Material in

lacquer	1.0 kg/h
wood	53.0 kg/h
furnishings and clothes	13.0 kg/h
body	65.0 kg/h
natural gas	37.1 kg/h
air for combustion (nat. gas)	675.0 kg/h
air for combustion (charge)	1504.0 kg/h
TOTAL	2348.1 kg/h

Material Out

ash	3.5 kg/h
H_2O from charge (free)	39.5 kg/h
H_2O from combustion (cellulose)	49.5 kg/h
H_2O from combustion (nat. gas)	79.5 kg/h
dry gases	2176.1 kg/h
TOTAL	2348.1 kg/h

Total H_2O = 39.5 + 49.5 + 79.5 = 168.5 kg/h

Total dry gases = 2955.4 kg/h

Moisture content in gases $\dfrac{168.5}{(2348.1 - 3.5)} \times 100 = 7.2\%$

Gross Heat Input

From charge	1,534,816 kJ/h
From natural gas	1,937,312 kJ/h
TOTAL	3,472,128 kJ/h

<u>Heat not available to raise temperature of the gases</u>

heat storage 2 x 501,893	=	1,003,786 kJ/h
sensible heat in ashes 3.5 x 0.92 x 785	=	2,528 kJ/h
Latent heat in H_2O 168.5 x 2463	=	415,016 kJ/h
TOTAL		1,421,330 kJ/h

Net heat available to raise the temperature of the gases
Q = 3,472,128 - 1,421,330 = 2,050,798 kJ/h

Temperature of the gases

$$\Delta T = \frac{Q}{(m.Cp)\ gas + (m.Cp)\ H_2O}$$

$$\Delta T = \frac{2,050,798}{(2176.1 \times 1.046) + (168.5 \times 2.09)} = 780°C$$

$$T = 780 + 15 = 795°C$$

The overall heat and mass balance shows a deficiency of heat and would suggest that the after burner input should be increased.

The temperature in the secondary chamber must be raised to 1000°C.

Therefore, new ΔT = 1000 - 15 = 985°C

$$Q = \Delta T\ [(mCp)\ gas + (mCp)\ H_2O]$$
$$Q = 985\ [(2176.1 \times 1.046) + (168.5 \times 2.09)]$$
$$Q = 985 \times 2,628 = 2,588,940\ kJ$$

The difference between the previously calculated "net heat available" (Q_1) and the newly calculated "net heat available" (Q_2) must be supplied by the afterburner in useful heat.

Useful heat to be supplied

$$Q = Q_2 - Q_1$$
$$Q = 2,588,940 - 2,050,798 = 538,142 \text{ kJ/h}$$

from Appendix A-4, page 53 1 m³ of natural gas supplies 15,500 kJ of useful heat when combusted at 1000°C with 20% excess air.

Volume of natural gas required:

$$\frac{538,142}{15,500} = 34.7 \text{ m}^3\text{/h}$$

Burner capacity required in secondary chamber is

$$(34.7 \times 37,256) + 700,413 = 1,993,196 \text{ kJ/h}$$

However, the previous calculation does not differentiate between the various stages in the cycle and therefore does not indicate peak requirements.

For satisfactory operation, a minimum draft of 0.25 cm W.G. at the charging door will be required. Depending on the configuration of the cremator chambers, the average pressure drop across the unit may be taken as 0.63 cm W.G., requiring a draft at the base of the chimney of 0.89 cm W.G. This would require a chimney height of 10.7 m, depending on chimney design and construction.

Dimensions of Chambers and Chimney

The physical dimensions of the primary chamber in a cremator are dictated by the size of the casket. Sufficient space should be provided for the burner flames.

Mixing Chamber

Weight of gases from primary chamber:

total dry gases	=	2,272.5 kg/h
total H_2O	=	162.0 kg/h
TOTAL		2,434.5 kg/h

Assume an average molecular weight for products = 29.

Number of kg moles of gases $\frac{2434.5}{29}$ = 83.95 kg moles/h

1 kg mole = 22.4 m^3 at 0°C and 101.3 kPa

Volume of gases @ 1000°C

$$83.95 \times 22.4 \times \frac{1000 + 273}{0 + 237} \times \frac{1}{3600} = 2.44 \ m^3/s$$

Velocity required for good mixing = 6.1 m/s

Required cross-sectional area $\frac{2.44}{6.1}$ = 0.4 m^2

Secondary Chamber

Weight of gases from mixing chamber	=	2434.5 kg/h
Products of combustion from afterburner	=	730.2 kg/h
TOTAL		3164.7 kg/h

Number of kg moles $\frac{3164.7}{29}$ = 109.13 kg moles/h

Total volume of gases @ 1000°C

$$109.13 \times 22.4 \times \frac{1273}{273} \times \frac{1}{3600} = 3.17 \ m^3/s$$

Velocity in secondary chamber 3.05 m/s

Required cross-sectional area $\frac{3.17}{3.05}$ = 1.04 m^2

Chimney

Since the heat loss from the chimney will depend on the type and thickness of the insulating material, the chimney height, the ambient temperature etc., and thus vary, a temperature drop of 55°C in the flue gases is assumed.

Volume of flue gases at 945°C

$$109.13 \times 22.4 \times \frac{1218}{273} \times \frac{1}{3600} = 3.03 \text{ m}^3/\text{s}$$

Acceptable gas velocity in the chimney is 9.14 m/s

$$\text{Cross-sectional area} = \frac{3.03}{9.14} = 0.33 \text{ m}^2$$

Chimney calculations, based on natural draft, have indicated that a minimum chimney height of approximately 10.7 metres above grade is required.

APPENDIX A-2

CONVERSION FACTORS

METRIC	IMPERIAL
Linear	
1 centimetre (cm) = 0.394 inches	1 inch = 2.54 cm
1 metre (m) = 3.28 ft.	1 ft. = 0.305 metres
1 kilometre (km) = 0.621 miles	1 mile = 1.61 km
Area	
1 sq. metre (m^2) = 10.76 sq. ft.	1 sq. ft. = 0.0929 m^2
1 sq. cm (cm^2) = 0.155 sq. ft.	1 sq. ft. = 6.45 cm^2
Volume (linear)	
1 cu. cm (cm^3) = 0.061 cu. in.	1 cu. in. = 16.39 cm^3
1 cu. metre (m^3) = 35.31 cu. ft.	1 cu. ft. = 0.0283 m^3
Volume (aqueous)	
1 litre (l) = 0.220 gals. Imp.	1 gal. Imp. = 4.54 litres
= 0.264 gals. U.S.	1 gal. U.S. = 3.78 litres
1 cu. metre (m^3) = 220.0 gals. Imp.	1 cu. ft. = 28.3 litres
1 cu. cm (cm^3) = 1 millilitre (ml)	
Weights	
1 gram (g) = 15.42 grains	1 grain = 0.065 grams
1 gram (g) = 0.00220 lbs.	1 oz. = 28.4 grams
1 kilogram (kg) = 2.20 lbs.	1 lb. = 454 grams
1 tonne (t) = 2205 lbs.	1 ton = 907.2 kg
Area Density	
kilograms/sq. metre (kg/m^2) = 1.4×10^{-3} p.s.i.	pound per sq. inch (p.s.i = 703.1 kg/m^2 = 70.31 cm. of H_2O
Pressure	
1 kilopascal (kPa) = 0.145 p.s.i.	1 p.s.i. = 6.89 kPa
1 pascal (Pa) = 1 Newton/m^2 = 9.87×10^{-6} atm.	

Heating Units

1 kilojoule (kJ) = 0.948 Btu   1 Btu = 1.055 kilojoules (kJ

1 Btu/lb = 2.3238 kJ/kg
1 Btu/lb.°F = 4.1828 kJ/kg.°C
1 lb/cu.ft = 16.03 kg/m^3
1 Btu/cu.ft = 37.2792 kJ/m^3
1 Btu/ft^2.hr. = 11.3563 kJ/m^2.h
1 Btu/ft^2.hr.°F = 6.2257 kJ/m^2.hr°C

Temperature

°Fahrenheit to °Celsius
(°F-32) x 0.556 = °C

°Celsius to °Fahrenheit
(°C x 1.8) + 32 = °F

Prefixes

Upper Case Symbols:

tera (T) = 10^{12}
giga (G) = 10^9
Mega (M) = 10^6

Lower Case Symbols:

kilo (k) = 10^3
hecto (h) = 10^2
deca (da) = 10^1
deci (d) = 10^{-1}
centi (c) = 10^{-2}
milli (m) = 10^{-3}
micro (u) = 10^{-6}
nano (n) = 10^{-9}
pico (p) = 10^{-12}
femto (f) = 10^{-15}
atto (a) = 10^{-18}

APPENDIX A-3

CALORIFIC VALUES OF VARIOUS MATERIALS (AS FIRED)

MATERIAL	H.H.V. BTU/lb.	kJ/kg
Lacquer	10,000	23,238
Wood	8,000	18,590
Cotton	7,200	16,731
Cellulose	7,526	17,489
Carbon	14,093	32,749
Hydrogen	60,958	141,654
Paper	7,500	17,428
Wax (paraffin)	18,621	43,271
Fat	16,700	38,807
Silk	8,400	19,520
Wool	9,000	20,914
Corpse	2,700	6,274
Rubber (foam)	13,000	30,209

APPENDIX A-4

ENGINEERING DATA FOR NATURAL GAS

The average analysis of natural gas as used in the Province of Ontario is as follows:

Component	% by Volume
CO_2	0.36
N_2	2.57
O_2	0.00
CH_4	91.46
C_2H_6	5.08
C_3H_8	0.43
$i\text{-}C_4H_{10}$	0.05
$n\text{-}C_4H_{10}$	0.04
C_5+	-
C_6+	0.01
	100.00

Average gross heat = 37,256 kJ/m^3

Density = 1.4 m^3/kg

Air required for combustion of 1 m^3 of gas

a) stoichiometric = 9.63 m^3

b) with 20% excess air = 11.56 m^3

Products of combustion from 1 m^3 of gas

	Stoichiometric air		20% excess air	
	Volume	Weight	Volume	Weight
CO_2	1.03 m^3	1.9833 kg	1.03 m^3	1.9833 kg
H_2O	2.00 m^3	1.5279 kg	2.00 m^3	1.5279 kg
N_2	7.62 m^3	9.1065 kg	9.14 m^3	10.9278 kg
O_2	-	-	0.41 m^3	0.5467 kg
TOTAL	10.65 m^3	12.6177 kg	12.58 m^3	14.9857 kg

Available heat, in kJ/m^3 of gas, based on latent heat of vaporization of water at 15°C has been compiled in Table A-4.

TABLE A-4 (METRIC)

Available heat from 1 m^3 of natural gas

Temperature °C	Available Heat, kJ Stoichiometric Air	Available Heat, kJ 20% Excess Air
50	33,075	33,004
75	32,687	32,549
100	32,305	32,100
125	31,945	31,680
150	31,595	31,271
175	31,218	30,829
200	30,871	30,427
225	30,515	30,006
250	30,151	29,583
300	29,413	28,721
350	28,664	27,849
400	27,912	26,966
450	27,146	26,072
500	26,365	25,165
550	25,578	24,250
600	24,783	23,321
650	23,975	22,375
700	23,092	21,347
750	22,322	20,450
800	21,499	19,493
850	20,655	18,512
900	19,808	17,523
950	18,953	16,527
1000	18,091	15,528
1050	17,230	14,525
1100	16,365	13,515
1150	15,460	12,469
1200	14,581	11,445
1250	13,681	10,396
1300	12,773	9,348
1350	11,876	8,302
1400	10,969	7,253
1600	7,317	3,009
1800	3,598	0.0
2000	0.0	0.0

TABLE A-4 (IMPERIAL)

Available heat from 1 cu.ft. of natural gas

Temperature °F	Available Heat, BTU Stoichiometric Air	Available Heat, BTU 20% Excess Air
100	892.9	891.9
150	881.3	878.3
200	869.7	864.7
250	858.9	852.0
300	848.5	839.9
350	837.2	826.7
400	827.0	814.8
450	816.2	802.1
500	805.4	789.5
550	794.3	776.5
600	783.3	763.7
700	760.9	737.6
800	738.3	711.1
900	715.2	684.2
1,000	691.8	657.0
1,100	668.1	629.3
1,200	644.0	601.2
1,300	617.7	570.5
1,400	595.1	544.2
1,500	570.1	515.1
1,600	544.8	485.7
1,700	519.5	456.2
1,800	493.8	426.3
1,900	468.1	396.4
2,000	442.5	366.5
2,100	415.5	335.3
2,200	389.3	304.8
2,300	362.3	273.4
2,400	335.3	242.1
2,500	308.6	211.1
3,000	172.4	52.9
3,500	33.0	-108.7

APPENDIX A-5

HEAT LOSS THROUGH WALLS AND HEAT STORAGE

In many heat loss calculations for furnaces, it is assumed that all materials have reached their equilibrium temperatures (steady state conditions).

However, in many cases a furnace is operated from a cold start and before equilibrium conditions can be reached, the process cycle is completed and the furnace shut down again.

Among various units, the cremator would fit this pattern, hardly ever reaching steady state conditions.

During the relative short period of operation of the unit, a considerable amount of heat will be stored in the firebrick, hence it is desirable to choose a refractory material with a low heat capacity.

After the furnace has been in operation for some time, the outside wall will reach a temperature at which the heat loss to the ambient air can no longer be ignored. Considering that the cremator is located inside a building, heat loss calculations may be based on natural convection (zero wind velocity). For convenience, Table A-5 may be used.

To calculate the heat storage in the cremator, the following information is required:

1. The specific heat (Cp) for each component of the wall in kJ/kg.°C;

2. The thickness of each component of the wall in metres;

3. The density of each component of the wall in kg/m^3; and

4. The inside wall temperature, the interface temperatures and the outside wall temperature in °C.

EXAMPLE:

Consider a two component wall consisting of 0.2 m firebrick and 0.075 m insulblock. The inside wall temperature is 1000°C.

Calculate the outside wall temperature, the interface temperature, the heat loss through the wall per 1 m^2 wall area and the heat storage in the wall per 1 m^2 wall area.

Data for Firebrick (for a mean temp. of 871°C)

Density = 1763 kg/m^3
Thermal conductivity k = 4.67 kJ/m.h°C
Specific heat Cp = 1.1712 kJ/kg.°C

Data for Insulblock (for a mean temp. of 427°C)

Density = 481 kg/m^3
Thermal conductivity k = 0.4981 kJ/m.h°C
Specific heat Cp = 0.9202 kJ/kg.°C

Solution

The general heat transfer equation is:

$$Q = \frac{T_1 - T_2}{\frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{L_3}{k_3} + \text{etc.}}$$

where Q = heat transferred through the wall in $kJ/m^2.hr$.

T_1 = inside wall temperature in °C

T_2 = outside wall temperature in °C

L_1 = thickness of first wall component in m.

L_2 = thickness of second wall component in m.

L_3 = thickness of third wall component in m.

k_1 = thermal conductivity of first wall component in $kJ/m.h\ ^\circ C$

k_2 = thermal conductivity of second wall component in $kJ/m.h\ ^\circ C$

k_3 = thermal conductivity of third wall component in $kJ/m.h\ ^\circ C$

Having two unknowns (Q and T_2) and only one equation, one of the unknowns must be assumed for a first trial.

Assume an outside wall temperature (T_2) of 150°C, then

$$Q = \frac{1000 - 150}{\frac{0.2}{4.67} + \frac{0.075}{0.4981}} = 4214\ kJ/m^2.h$$

From Table A-4, a heat loss of 4214 $kJ/m^2.h$ in still air at 21°C corresponds to approx. 109°C, therefore the assumed temperature of 150°C was too high. Assume a lower outside wall temperature which is slightly higher than 109°C, say T_2 = 114°C

$$Q = \frac{1000 - 114}{\frac{0.2}{4.67} + \frac{0.075}{0.4981}} = 4581\ kJ/m^2.h$$

From Table A-4, the heat loss at 114°C would be 4581 $kJ/m^2.h$ and therefore the second trial is correct.

When calculating the interface temperature, it is assumed that all wall components have reached equilibrium temperatures. Thus, the amount of heat passing through the first wall component must equal the amount of heat passing through the second wall component and must also equal the amount of heat lost to the ambient air which in this case is 4581 $kJ/m^2.h$.

Let x = interface temperature
For the firebrick section,

$$Q = \frac{T_1 - x}{\frac{L_1}{k_1}}$$

$$x = T_1 - (Q \times \frac{L_1}{k_1}) = 1000 - 4581 \times \frac{0.2}{4.67} = 803.8°C$$

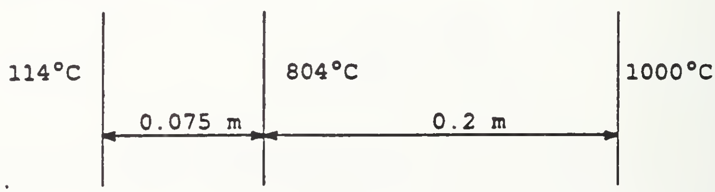
Although it is sufficient to consider any one of the wall components, a check can be made by considering another wall component.

For the insulblock section,

$$Q = \frac{x - T_2}{\frac{L_2}{k_2}}$$

$$x = T_2 + (Q \times \frac{L_2}{k_2}) = 114 + 4581 \times \frac{0.075}{0.4981} = 803.77°C$$

Interface temperature is 804°C



For heat storage calculations, the mean temperature for each component is used.

Heat storage:

$$Q = m_1 \times Cp_1 \times (Tm_1 - T_a) + m_2 \times Cp_2 \times (Tm_2 - T_a)$$

Where Q = total heat storage per 1 m^2 wall area in kJ/m^2

m_1 = weight of first wall component corresponding to 1 m^2 wall area in kg.

m_2 = weight of second wall component corresponding to 1 m^2 wall area in kg.

Cp_1 = specific heat for first wall component at mean temperature Tm_1 in kJ/kg.°C

Cp_2 = specific heat for second wall component at mean temperature Tm_2 in kJ/kg.°C

Tm_1 = mean temperature of first wall component in °C

Tm_2 = mean temperature of second wall component in °C

T_a = ambient temperature in °C

$$m_1 = 1\ m \times 1\ m \times 0.2\ m \times 1763\ kg/m^3 = 352.6\ kg.$$

$$Tm_1 = \frac{1000 + 804}{2} = 902°C$$

$$m_2 = 1\ m \times 1\ m \times 0.075\ m \times 481\ kg/m^3 = 36\ kg.$$

$$Tm_2 = \frac{804 + 114}{2} = 459°C$$

$$Q = 352.6 \times 1.1712\ (902 - 21) + 36 \times 0.9202\ (459 - 21)$$

$$= 363{,}822 + 14{,}510 = 378{,}332\ kJ/m^2$$

To account for the heat storage in a heat balance (usually on an hourly basis), the amount of heat stored per hour is required.

Many refractories and brickwork take 8 hours or more to reach equilibrium conditions, therefore the hourly heat storage in this example is

$$q = \frac{378{,}332}{8} = 47{,}292\ kJ/m^2.h$$

where q = hourly heat storage per 1 m^2 area.

TABLE A-5 (METRIC)

HEAT LOSS IN STILL AIR, kJ/m².h

Outside Wall Temp. °C	Ambient Air Temp. 5°C	Ambient Air Temp. 21°C	Ambient Air Temp. 38°C
5	0	-	-
10	114	-	-
15	318	-	-
20	522	0	-
25	687	159	-
30	840	295	-
35	1022	454	0
40	1249	650	68
45	1488	847	249
50	1732	1079	477
55	1953	1329	684
60	2158	1590	909
65	2413	1738	1113
70	2669	1987	1317
75	2924	2243	1561
80	3214	2498	1851
85	3549	2782	2129
90	3770	3066	2385
95	4088	3350	2640
100	4417	3673	2919
105	4753	3952	3271
110	5110	4259	3577
115	5417	4667	3884
120	5769	4985	4236
125	6166	5348	4570
130	6562	5733	4938
135	6973	6104	5309
140	7393	6507	5690
145	7802	6933	6098
150	8211	7311	6514
155	8682	7761	6953
160	9142	8211	7393

TABLE A-5 (IMPERIAL)

HEAT LOSS IN STILL AIR, BTU/FT².h

Outside Wall Temp. °F	Ambient Air Temp. 40°F	Ambient Air Temp. 70°F	Ambient Air Temp. 100°F
40	0	-	-
50	10	-	-
60	30	-	-
70	50	0	-
80	65	20	-
90	80	30	-
100	100	50	0
110	125	68	15
120	145	90	38
130	170	115	58
140	190	135	80
150	215	155	100
160	240	180	120
170	265	205	145
180	295	230	175
190	320	260	200
200	350	285	225
210	382	318	250
220	415	345	285
230	450	375	315
240	480	415	345
250	515	445	380
260	555	482	412
270	593	520	450
280	635	555	485
290	675	600	525
300	715	635	565
350	940	855	780
400	1200	1120	1030
450	1500	1410	1330
500	1830	1740	1670

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